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REPORT NO. 753

SENSE MODE AND COUPLING IN A VIGILANCE TASK

(Progress Report)

By

Lt Colonel Jimmy L. Hatfield, MSC
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ABSTRACT

SENSE MODE AND COUPLING IN A VIGILANCE TASK

OBJECTIVE

As noted by the diverse findings, especially between visual and auditory vigilance tasks, a decrement in performance during a vigilance task may be due to changes in the observer's criteria (β) or to decreased sensitivity (d'). Due to the unique operating characteristics of each sense modality (coupling), it is certainly plausible that performance decrement may be produced by different underlying mechanisms. The generally low correlations of performance between sense modes support this hypothesis. These research issues must be resolved before the term vigilance can be used to represent a general trait or a fundamental characteristic of the individual.

METHOD

This investigation examined the performance of thirty-six subjects on three 90-minute vigilance tasks: a closely coupled auditory task, a closely coupled visual task, and a loosely coupled visual task. Subjects were assigned to a single or multiple signal group ($N = 18$). Response measures for signals were available in three basic forms: hits, false alarms, and response latency. In addition, the parameters of signal detection, d' and β, were derived from the data. Correlation coefficients were computed on all of these measures to determine the correlation of performance between tasks.

SUMMARY

There was a significant decrease in hits and false alarms with increasing time on task, regardless of sense mode and coupling conditions, or the number of signal intensities. The finding that the detection probability for the auditory signals was higher than for the visual signals is in agreement with prior research, even when attempts have been made to equate difficulty level between sense modes. In general, the experimental evidence confirms the prediction that when detection rate decreases, reaction time increases; and that as fewer signals are detected, the observer takes longer to respond to those

signals detected. The consistent rank order relationship between the stimulus conditions clearly suggests that there are uniform trends among conventional response measures. The auditory task had the greatest number of hits, fewest false alarms, and the shortest response time. Conversely, the loosely coupled visual task was characterized by the fewest number of hits, most false alarms and the longest latency.

There was a significant decline in sensitivity (d') with increasing time on task for the closely coupled tasks, regardless of the sense mode involved. However, d' remained fairly stable for the loosely coupled visual task. This finding is not compatible with the explicit assumptions of conditioning, reinforcement, or observing response theory. Rather, it is tentatively postulated that the irrelevant observing responses may actually inhibit habituation effects, and thereby permit a relatively stable sensitivity level to be maintained throughout the vigilance session.

The subject's criterion (β) of what constitutes a signal appears to exert a major influence in monitoring tasks. In this experiment, β values increased significantly during the vigilance session, irrespective of number of signal intensities, sense mode or coupling conditions. There was a tendency, therefore, for the observer to adopt a more conservative mode of responding with increasing time on task.

Orthogonal comparisons of that portion of the variance due to stimulus conditions clearly establish coupling effects as a critical independent variable. It is suggested that a lack of control of coupling effects, rather than sense mode specificity, may have confounded the interpretation of the results between visual and auditory tasks.

Numerous significant correlation coefficients were obtained but it was difficult to identify and isolate uniform effects for a specific variable. The moderate, but not statistically significant, correlations of d' and β between auditory and visual tasks were particularly interesting and potentially of theoretical importance. These cross-modality correlations may signify a cognitive or other central component of signal detection transcending modalities.

Current methodological problems associated with this area of research are discussed in detail.

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INTRODUCTION

During the past 25 years, the research effort in vigilance has been directed mainly at identifying the factors that affect the vigilance decrement. A broad range of variables related to vigilance performance has been investigated. There are several critical surveys of the existing literature, with emphasis being given to the organization of experimental results under the several theoretical hypotheses which have been advanced in explanation of the data (6, 10, 11, 19, 24, 32). Thus, the development of a framework for organizing the accumulation of empirical findings has not been neglected and it is now possible to distinguish a number of explanatory systems. Mackworth (46) has suggested that a watch-keeping session is comparable to a conditioning situation and that a cumulative inhibition is generated that increases with successive detections. Deese (21) and Baker (2) explain the performance decrement in terms of adjustment of subjective expectancies to the actual experimental schedule of signals. Another approach (30, 36, 45, 48, 49) considers that a varied background of stimulation is necessary to maintain normal activation or arousal, and suggests that the performance is attributable to a progressive lowering of activation level in the monotonous monitoring situation. Broadbent (10) advanced the hypothesis that an individual performing a monitoring task initially behaves as a filter biased to receive information, as from the signal display, and that with time on task there is an increasing tendency to temporarily shift to receive other, irrelevant information. Holland (31) and Jerison and Pickett (33) have taken the position that: (1) subjects must perform "observing responses" in order to detect signals, (2) the detection of a signal is somehow reinforcing, and (3) since this reinforcement occurs only occasionally, the observing responses tend to extinguish with time on task.

The variety of theoretical and quasi-theoretical interpretations that have been applied to vigilance phenomena encompasses most of the major theories in psychology. These include several variations of conditioning, expectancy, drive (physiological), and information theories of behavior. None of the systems are sufficiently comprehensive to include all of the relevant aspects of the problem. Unfortunately, each of these theories appear to have unique merit in explaining only certain of the experimental findings. Moreover, they are not mutually exclusive.

RESEARCH PROBLEM

Egan, Greenberg, and Schulman (22), viewing the monitoring situation within the framework of signal detectability theory have suggested that there is no real decrement in operator efficiency on vigilance tasks; instead, there is a progresive change in the observer's criterion in the direction of greater conservativeness in responding such that later in a monitoring period there is a reduced tendency to report faint signals and also a reduced tendency to report environmental or physiological noise as a signal.

In recent years, numerous experiments have demonstrated the relevance and applicability of the theory of signal detectability to the study of vigilance phenomena. However, research which has related the measures of sensitivity (d') and criterion (β) values to performance in visual and auditory tasks has been largely contradictory. As noted by the diverse findings, a decrement in performance during a vigilance task may be due to changes in the observer's criteria (12, 22, 38) or to decreased sensitivity (40, 42, 43, 44). Unfortunately, the experimental designs utilized by the latter group of investigators did not always permit the computation of β values. As a result, it is most difficult to determine whether changes in sensitivity or the observer's criteria more accurately reflect the performance obtained in visual and auditory vigilance tasks. Due to the unique operating characteristics of each sense modality, it is certainly plausible that there might be two or more types of vigilance "decrements" produced by different underlying mechanisms. In some vigilance tasks there may be a true decline in effective sensitivity. This might be reflected primarily in a change in detections, especially in a "loosely coupled" task like the Mackworth Clock Test and related visual tasks, in which the subject may easily make a response incompatible with observation of the display. On other tasks involving more "closely coupled" responses, e.g., auditory tasks, in which observers could not readily fail to receive stimulation from the display, the apparent decrements might be due to changes in the observer's criteria.

It is also apparent that manipulations of difficulty levels in prior research involving two different sense modes has been largely unsuccessful. This is especially true if both visual and auditory vigilance tasks are involved. The experiments involving more than one modality have clearly demonstrated the differential effects upon task performance as a function of differences in task difficulty.

Few vigilance studies have examined the performance of observers monitoring single and multiple signal levels. This manipulation is

of special importance because in the real world situation most signal levels are variable. A specific question of interest is whether performance efficiency is approximately the same for single and multiple signal-level conditions, particularly when identical signal intensities have occurred.

The combined results of prior research have shown that the reliabilities of individual performances on a particular task are high, that the correlations between alerted (pretest and posttest) and watch (vigilance) performances are high, but that the correlation between individual performances from one task or sensory mode to the other is very low (15, 16, 17). This latter finding must be resolved before the term "vigilance" can be used to represent a general trait or a fundamental characteristic of the individual.

METHOD

Preliminary Study. Before the main experiment, a pilot study was conducted to determine an index of discriminability for each experimental condition. The primary purpose was to obtain performance data which could be used in determining comparable levels of detectability for the visual and auditory signals to be used in the main experiment. Subjects were given extensive practice and a one-hour vigilance task on each sense modality. Test conditions were identical with the auditory and visual vigilance tasks to be used in the main experiment.

For the auditory task, difficulty levels for the Difficult, Moderate, and Easy signals were defined as being increments of 0.8, 1.3, and 1.8 db (SPL), respectively. Prior research on comparable detection and vigilance tasks (7, 26, 37, 38, 53) indicates that .4 - .8 db increment shifts can produce sizeable differences in detection performance. Using this performance data, specifically the d' values, the physical stimulus values for the visual signals were adjusted accordingly in order to provide a comparable task for each stimulus condition (Table 1, next page). Pilot data indicated that difficulty levels were matched between the three stimulus conditions, within a ± .35 d' range (Table 2, next page).

Main Experiment.

Subjects. Thirty-six volunteer male personnel assigned to the US Army Medical Research Laboratory were employed as subjects in this experiment. Since these individuals had recently completed the standard induction physical examination, no rigorous screening procedure was necessary. Subjects were randomly assigned to a one or three

TABLE 1

Physical Stimulus Values for Visual Vigilance Tasks

Stimulus source	Closely coupled visual task (Ft. -candles)	Task Difficulty	Loosely coupled visual task (Ft. -lamberts)
100 watt (n-s)	5.0		190
100/40 watt	6.0	Difficult	235
100/60 watt	7.5	Moderate	245
100/100 watt	9.5	Easy	310

TABLE 2

Mean d' Values for Each Stimulus Condition (N = 10)

Task Difficulty

Stimulus condition	Difficult	Moderate	Easy
Auditory (closely coupled)	1.34	2.40	3.76
Visual (closely coupled)	1 17	2.33	3.99
Visual (loosely coupled)	.99	2.29	3.89

signal level group, 18 subjects in each. There were no specific age controls, because prior research (20, 52, 54) has indicated that there is little relationship between age differences and performance on a vigilance task. The subject population was limited to Caucasians,

however, in order to eliminate the effects of skin pigmentation of the eyelids in the closely coupled visual task.

Vigilance Tasks. Auditory session (closely coupled): Each subject listened to a series of pulses of white noise, having an intensity of 70 db (SPL), a duration of .5 sec, initiated 2.5 sec apart. Aperiodically, increments in intensity were added to the pulses. These more intense pulses were defined as signals and the subject's task was to acknowledge detection by pressing a telegraph key. Responses within 2.5 sec after initiation of the signal were scored as detections; no response during this interval as a miss; other responses as false alarms.

Visual session (closely coupled): Subject's eyelids were taped closed with transparent plastic tape to eliminate eyeblink and increase "coupling" (19, 23, 31, 33, 34) and minimize the effects of "observing responses" (3, 9, 31, 33, 34). It is entirely plausible that the low correlations obtained on vigilance performance in different sense modes has been primarily due to these confounding variables. Each subject sat in a straight-back chair with arm rest, approximately 4 ft from a light source. The room was dark, except when the light source was switched on for 0.5 sec intervals during the experimental session. Illumination was provided by various combinations of four incandescent bulbs in an L-shaped plywood box. The open sides of the box permitted light pulses to be reflected on a flat white wall. Since the light source was located on the floor of the Industrial Acoustics Company (IAC) booth (bottom of the diffusing area), there was a vertical gradient of illumination in the immediate area of the light source. However, subject's eyes were taped closed and this gradient was not perceptible. The non-signal light pulses were produced by a single, shaded 100-watt bulb. Occasionally, increments in intensity were added to the non-signal pulses. These more intense pulses served as signals and the subject's task was to respond by pressing a telegraph key. Recording of responses was identical to that previously mentioned for the auditory session.

Visual session (loosely coupled): Each subject sat in a straight-back chair with arm rest, approximately 4 ft from a light source located at eye level in a black plywood box. The subject was required to detect a change in the brightness of a light appearing in a 1-inch ground-glass (neutral density filter) covered aperture. Ambient illumination in the test room was furnished by the overhead ceiling lights in the IAC room.

Procedure. Each subject was available for four consecutive days of testing; an orientation and practice session on the first day and a 90-min watch on the next three days (auditory or visual conditions in counterbalanced order between subjects). On the first day, subjects were given instructions about the tasks and a complete briefing on all experimental requirements. Immediately following this orientation, all subjects were required to complete two brief watch periods on each vigilance task. These practice sessions were identical with the auditory and visual conditions to be used in the experimental sessions, except that each watch period was brief (5 min) and the signal rate high (20 signals per 5 min). There was a one-minute rest period between each practice session for each stimulus condition and a 5-min rest period between the sessions for the different sensory modes. Immediate knowledge of results was given for each signal (by the experimenter using the booth intercom system). Subjects in Group I (one signal level) were required to detect a signal of Moderate difficulty, whereas subjects in Group II (three signal levels) were presented with an equal number of Difficult, Moderate, and Easy signals during each session.

Each 90-min watch period was preceded by a 5-min warm-up period during which immediate knowledge of results was given for each signal. Subjects were given a 2-min rest period followed immediately by the 90-min main watch. Signal rate averaged one per minute, with the intersignal interval varying from 10-120 sec. The distribution between intervals was rectangular, with a mean intersignal interval of 60 sec. Within the limits of the interval range, signal occurrence was random with the restriction that five signals of each difficulty level (for subjects in Group II) must occur within each 15-min period of the watch. No knowledge of results was presented in these experimental sessions.

Apparatus. The experiment was conducted in an IAC sound-shielded room in which over-all ambient sound level is approximately 30-50 db (SPL). The random noise for the auditory stimuli was generated by a random-noise generator (Grason-Stadler, model 455-B) and presented through a pair of earphones embedded in Grason Stadler, model HD-30 muffs, the latter producing an additional 15 to 45 db attenuation (frequency dependent) of this ambient sound. Auditory signal intensities were adjusted to the three difficulty levels by Daven variable attenuators, model VT-795-G. The signal and non-signal pulses were measured (calibrated) with a Brüel and Kjaer 6 cc coupler, using a model 4132 Brüel and Kjaer condenser microphone. The light source (brightness - illumination) was furnished by an appropriate

combination of incandescent light bulbs contained in a plywood box. Illumination (brightness) levels were measured by a Spectra Brightness Spot Meter for the loosely coupled visual task and a Weston Foot-Candle Meter (model 614) for the closely coupled visual task. Since the subject's eyes were taped closed in the closely coupled visual task, the exact values of illumination transmitted to the cornea are unknown, but the ratios between intensities presumably remained constant for each subject. Duration of signals was controlled by Hunter timers (models 100-B and 111-B) and the intersignal intervals by a Gerbrands program timer (model 1A - 4 mm).

Design. The experimental design was a 3 x 6 x 2 mixed factorial design with repeated measures on the first two factors (stimulus condition - "closely coupled" Auditory, "closely coupled" Visual, "loosely coupled" Visual and time blocks). Two groups of 18 subjects each define the third factor (number of difficulty levels). The relationships of primary interest are: number of difficulty levels (between subjects), auditory vs "closely coupled" visual vs "loosely coupled" visual (within subjects), and time on task (within subjects). Time on task was divided into six 15-min time blocks for analyses.

Response measures for signals occurring in each of the two modalities were available in three basic forms: (1) correct detections (Hits), (2) errors of commission (False Alarms), and (3) response time (Latency). However, the derived dependent measures of primary interest are d' and β, which were readily computed by methods described in prior research (12, 34). Pearson product-moment correlation coefficients across sensory modalities and coupling conditions were computed on all of these measures.

RESULTS

In order to present an over-all view of the major findings and to facilitate comparisons with prior research, the data are summarized into five categories: (1) conventional measures, (2) signal detection measures, (3) orthogonal comparisons, (4) correlations of performance, and (5) number of signal intensities. One and three-signal level data are presented separately, since most prior research has employed only one signal-to-noise intensity ratio within a vigilance session.

Although analyses were performed in terms of the 3 x 6 x 2 complete design (35, pg. 292), supplementary A x B x S analyses (35, pg. 237) were performed to permit more detailed examination of variables

associated with stimulus conditions and time on task. Orthogonal comparisons (57, pg. 65) were performed to establish the relative importance of, and functional relationships between, sense mode specificity and coupling (nature of the task). Pearson product correlations were computed on all dependent measures to determine the correlations of performance between visual and auditory tasks.

Conventional Measures. Figures 1-6 present curves for mean number of Hits, False Alarms and Latency measures. As time on task increased, the number of detections and false responses both exhibited a general downward trend; whereas latency showed a marked increase. The rank order of stimulus conditions was fairly uniform, with the auditory task producing the highest level of performance, and the loosely coupled visual task producing the lowest. The closely coupled visual task maintained an intermediate position and exhibited the greatest variability, particularly when subjects were observing for three signal intensities within a vigilance session.

Hits. Figures 1 (below) and 2 (next page) show the mean number of detections in successive 15-min periods. At one signal

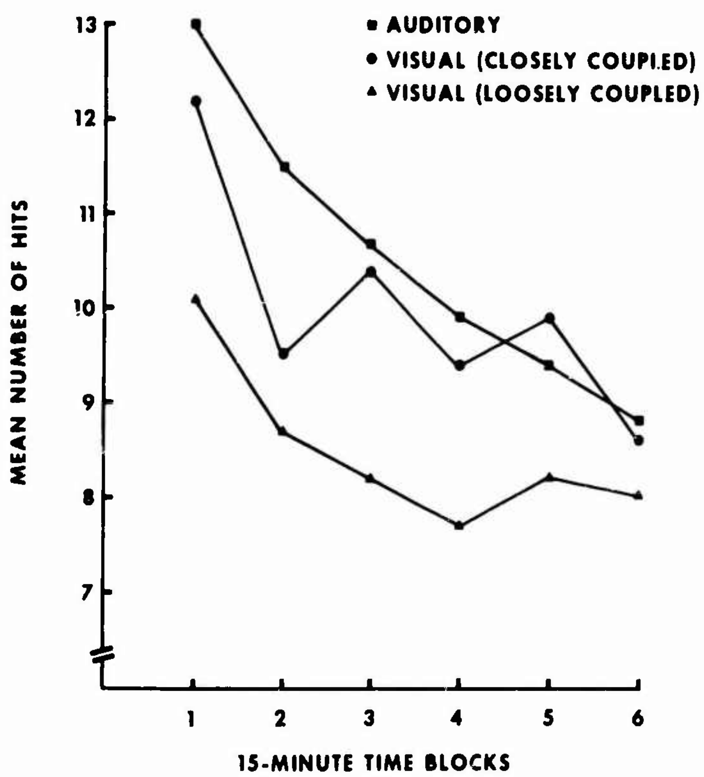

Fig. 1. Mean number of signals detected by the one signal level group.

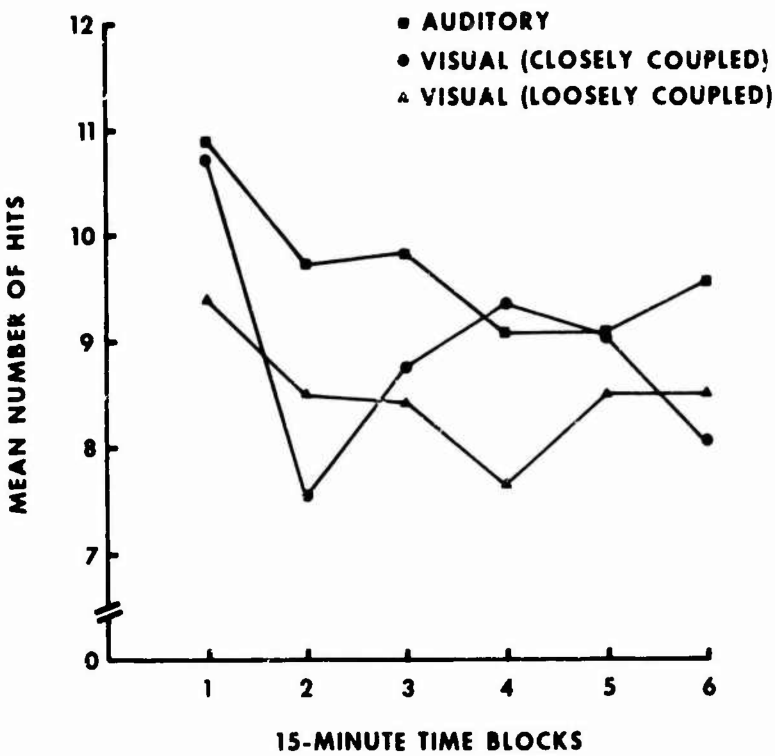

Fig. 2. Mean number of total signals detected by the three signal level.

level, differences between stimulus conditions were highly significant ($p < .005$); whereas differences between curves were not significant for the three signal level group. However, both groups detected most signals in the auditory condition and the fewest in the loosely coupled visual task. The closely coupled visual task generally occupied an intermediate position, but clearly exhibited the most variability. For both groups, the decline in hits with increasing time on task was significant ($p < .001$). Stimulus conditions x Blocks interaction was significant ($p < .05$) for the one signal level group.

False Alarms. Figures 3 and 4 (next page) present the mean number of false detections over successive time blocks. The differences between stimulus conditions and the downward trend with increasing time on task were highly significant ($p < .001$). The primary characteristic of these curves is the sharp decline in false alarms during the first 30 min of the session followed by a more or less gradual decline during the remaining periods. As compared with mean number of hits, there is an inverse relationship in the rank order of stimulus conditions, i.e., subjects exhibiting the largest number of hits on the auditory task also made fewer false alarms.

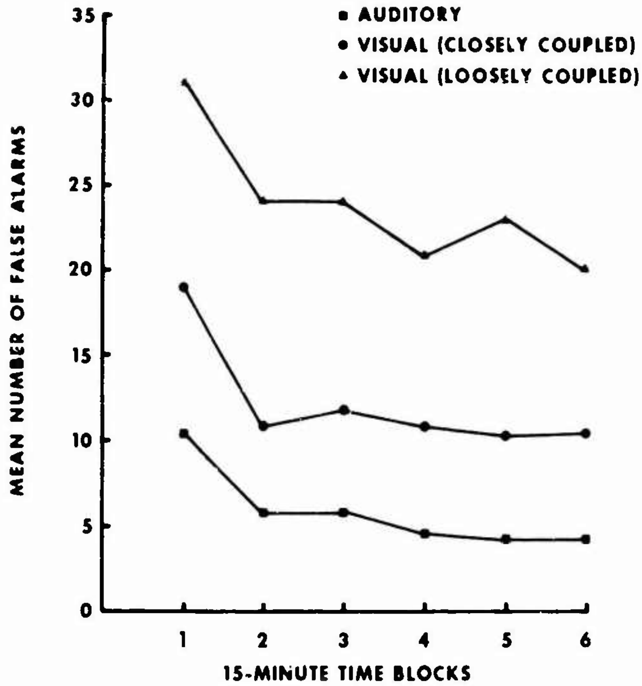

Fig. 3. Mean number of false alarms by the one signal level group.

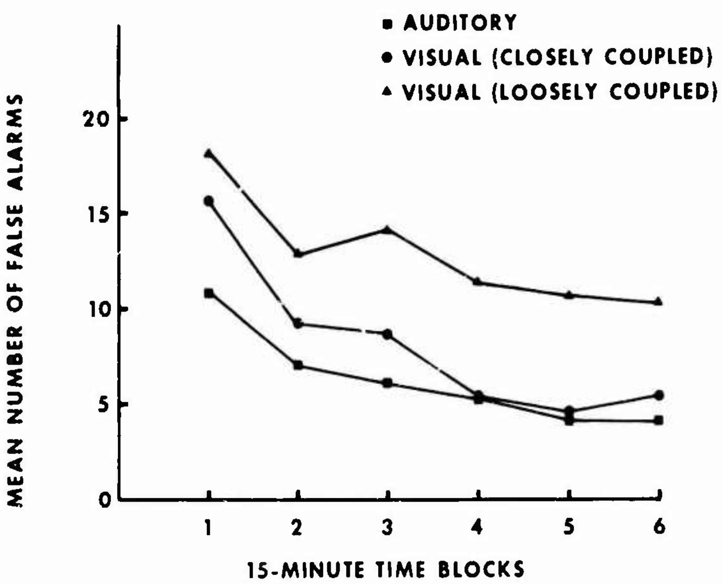

Fig. 4. Mean number of total false alarms by the three signal level group.

Latency. Latencies for each group are summarized in Figures 5 and 6 as a function of successive 15-min periods. The curves show an over-all increase in latency with time on task.

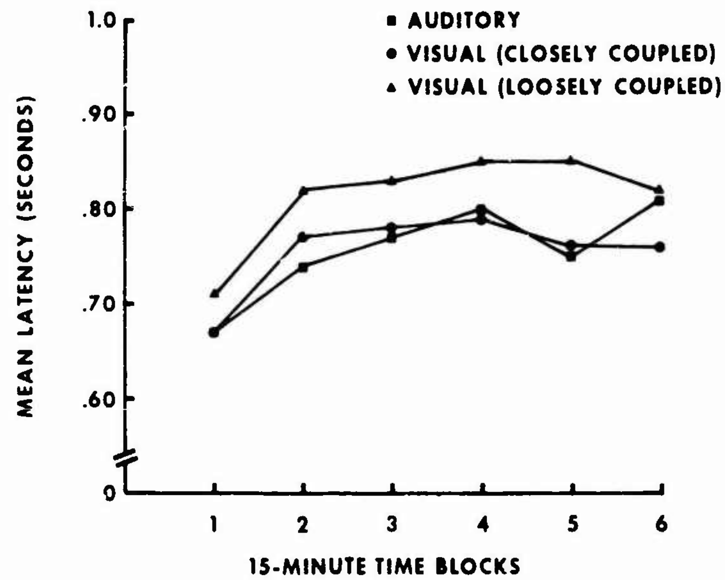

Fig. 5. Mean response latency by the one signal level group.

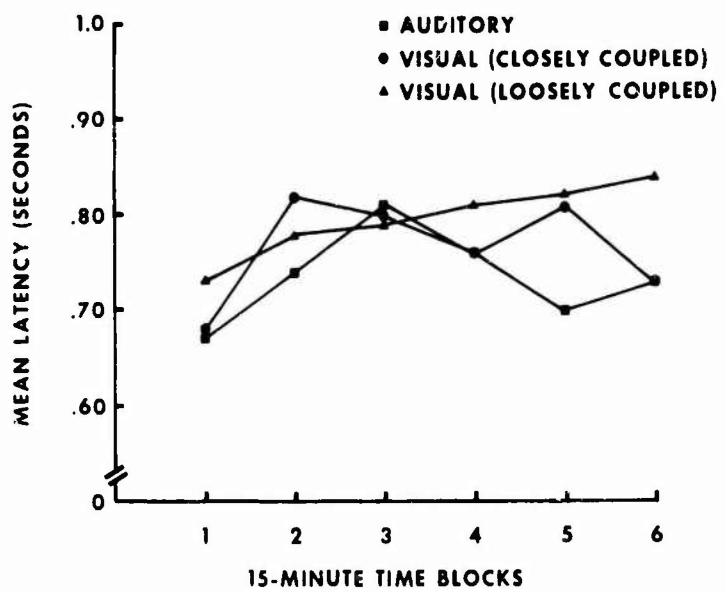

Fig. 6. Mean response latency for the three signal level group.

This increase is significant for both groups, one signal level ($p < .001$) and three signal levels ($p < .005$). Differences between stimulus conditions were not significant for either grou..

The preceding data indicate a relativelv consistency between the several conventional measures. As time on task increases, there is a significant decrease in hits and false alarms ($p < .001$) and a corresponding increase in response latency ($p < .005$). Further, there appears to be a consistent, rank order of stimulus conditions based upon difficulty of discrimination. The reason for considerable variability in the closely coupled visual task cannot be established.

Signal Detectability Measures. The relevance and applicability of the theory of signal detectability (TSD) to the study of vigilance phenomena has been well established and its potential theoretical significance documented (11, 26, 53). Additionally, signal detection theorists are currently expanding and elaborating the basic structure of the theory to include research with undefined observation intervals and temporally unstructured detection experiments (25). However, past research which has sought to relate the measure of sensitivity (d') and criterion (β) shift to performance in visual and auditory vigilance tasks has been largely contradictory. It was felt that by deriving both d' and β values from the data of the present experiment, some progress toward resolving these contradictions might be achieved.

There are methodological difficulties involved in the transformation of the data. Specifically, when proportions of detections are 0% or 100% or the percentages of false alarms are 0%, it is necessary to assign arbitrary percentages halfway between the observed 0% and 100% value and the next possible value. Such a procedure has been described by Jerison, et al (34) and permits an estimate of d' and β to be computed for vigilance data. There are additional problems associated with the three signal level group; namely, the assignment of false alarms to a specific intensity level. Therefore, it is necessary to compute an average sensitivity (d') and criterion level (β) for the three signal levels. While there is no precedent for this procedure, the technique seems reasonable since the Moderate intensity values were equated prior to the main experiment ($\pm .11$ d') and the Easy and Difficult intensity levels spaced approximately the same d' distance apart. This procedure will not permit a d' or β comparison of Moderate signal intensities (between groups) but does offer an opportunity to examine trends in total or over-all sensitivity and criterion values for each group.

Shown in Figures 7 and 8 (next page) are mean d' values for each 15-min period. There were significant differences between stimulus

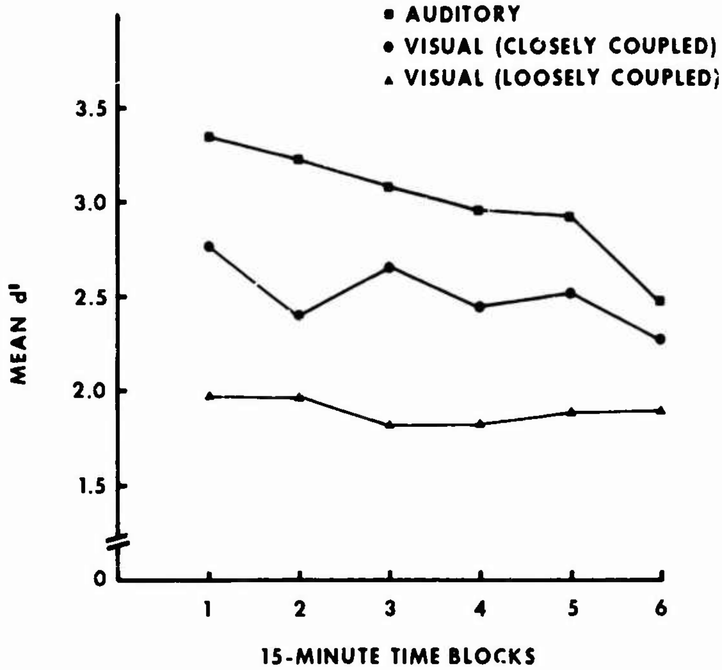

Fig. 7. Mean d' values for signals of moderate difficulty (one signal level group).

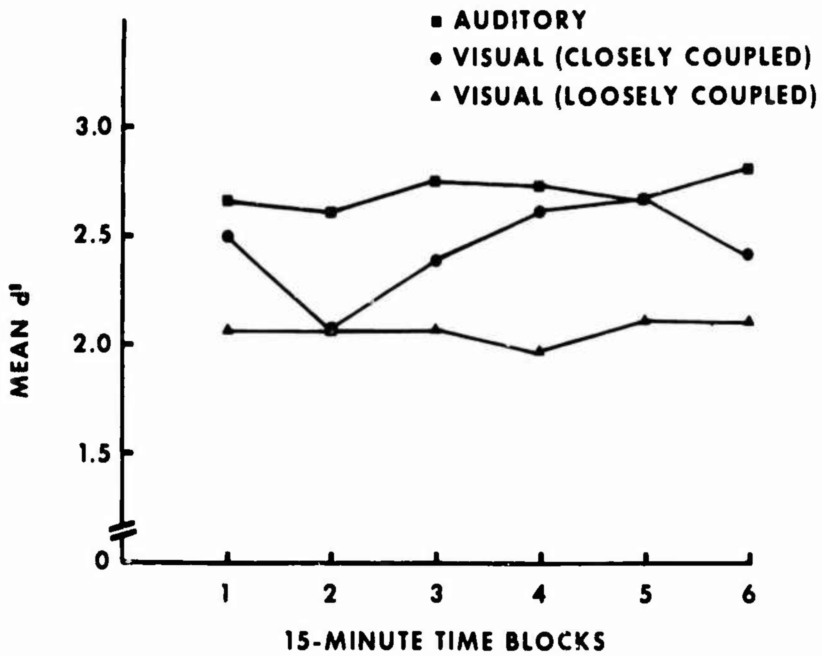

Fig. 8. Mean d' values for each stimulus condition (Easy, Moderate, and Difficult signals combined).

conditions for both groups ($p < .001$), and a significant decline in sensitivity for the one signal level group ($p < .005$). However, the slopes are not uniform, as evidenced by the Stimulus Conditions x Time Blocks interaction ($p < .05$). The nature of these effects are clearly shown in Figure 7, e.g., the d' value in the loosely coupled visual task is fairly uniform throughout the vigilance session, but the two closely coupled tasks show a gradual decline in sensitivity.

Mean criterion indexes (log β) are presented in Figures 9 (below) and 10 (next page). The underlying data were quite variable and contained a few extreme scores in each condition. Therefore, β's were transformed to their common logarithms prior to multivariate analysis. Differences between stimulus conditions and effects over time blocks were highly significant ($p < .001$). Stimulus Conditions x Time Blocks interaction was not significant for either group. The differences between curves and the uniform increase in β with time on task are readily apparent.

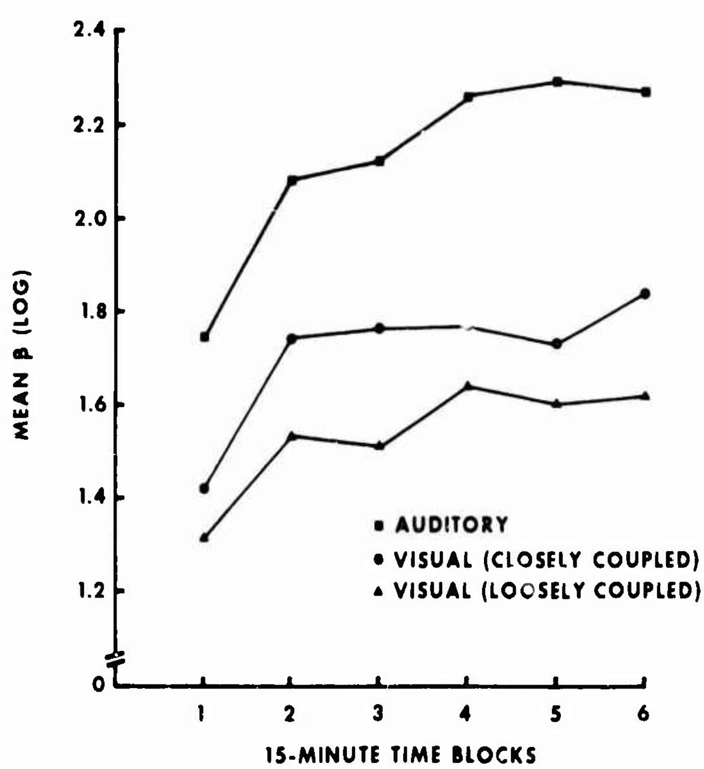

Fig. 9. Mean β values for signals of moderate difficulty (one signal level group).

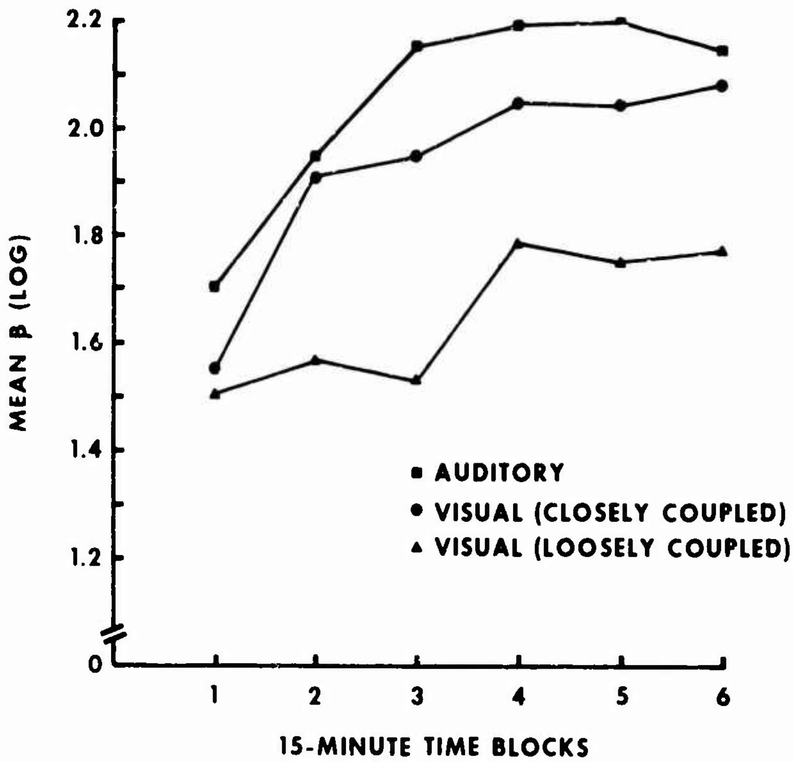

Fig. 10. Mean β values for each stimulus condition (Easy, Moderate, and Difficult signals combined).

If subjects are observing for signals at a constant signal-to-noise intensity ratio, it appears that sensitivity declines with increasing time on task for the closely coupled tasks, regardless of the sense mode involved. Sensitivity associated with the loosely coupled visual task remains fairly stable throughout the vigilance session. Sensitivity does not show a significant decline over time periods for those subjects that are required to detect three signal-to-noise intensity ratios as critical signals.

Criterion values, on the other hand, increase significantly during the vigilance session for both groups, irrespective of number of signal intensities, sense mode or coupling conditions. There was a tendency, therefore, to adopt a more conservative mode of responding with increasing time on task.

Orthogonal Comparisons. In order to further explore the effects of sense mode specificity and coupling on performance in vigilance tasks, orthogonal comparisons were computed on that portion

of the variance attributable to stimulus conditions. First, sense mode effects were determined by comparing the treatment means for the closely coupled auditory and closely coupled visual task. In this case, coupling was held constant and sense mode varied. If sense mode was not significant, the effects of coupling were examined by comparing the loosely coupled visual task with the average of the auditory and closely coupled visual tasks. If sense mode was significant, the comparison between closely and loosely coupled visual tasks was performed to estimate coupling effects. Thus, only two independent tests were computed in order to reduce the probability of a Type I error. Other comparisons are, of course, feasible. As an example, for the obtained β values on the one signal level group (Fig. 9), it is obviously more desirable to test for coupling effects initially (comparison between closely and loosely coupled visual tasks).

Table 3 includes F_{obv} values of each group on all dependent measures. This F ratio has one degree of freedom for the numerator and 321 degrees of freedom for the denominator. For these data the critical value is $F_{.99}(1,321) = 6.63$.

TABLE 3

Orthogonal Comparisons Between Stimulus Conditions to Determine Sense Mode and Coupling Effects

Stimulus Condition	Dependent Measure				
	Hits	False Alarms	d'	β	Latency
	One Intensity Level				
Sense Mode	.45	2.86	8.09**	39.37**	.0006
Coupling	13.76**	20.99**	11.60**	3.85	6.05*
	Three Intensity Level				
Sense Mode	.24	1.50	3.7	1.9	1.02
Coupling	.35	16.89**	18.94**	17.6**	2.80

F_{obv} values of each group of subjects on all dependent measures.

Critical value is $F_{.99}(1,321) = 6.63$.

*$p < .05$

**$p < .01$

At one intensity level, coupling effects account for a significant portion of the variance in four out of five measures; whereas, sense mode effects are largely restricted to the detection measures, d' and β. If subjects, however, are required to observe for three intensity levels, the significant effects of coupling are equally dramatic, but in this case, sense mode differences did not account for a significant portion of the variance on any of the five measures.

Correlations of Performance. Investigations concerned with correlations of performance between visual and auditory vigilance tasks have generally reported low correlations (15 - 19). These studies have largely emphasized the mode specificity of individual performances and have suggested that performance on one sense mode could not be predicted accurately from performance on another. Further, the findings have argued against the existence of a general mechanism as well as the status of vigilance as a general personality characteristic of the individual which determines the level of his performance regardless of the task. It should also be noted that percentage of correct detections has been the primary response measure.

In order to explore these possible relationships within the context of the present experiment, scores for each individual were computed for each 90-min session as follows: (1) total number of hits and false alarms, (2) mean response latency, and (3) over-all d' and β values. Pearson product-moment correlations were then computed between individual performance scores for each stimulus condition. Correlations for β were computed after a normalizing log transformation. These data have been summarized in Table 4 (next page). The critical importance of coupling effects and the selection of dependent measures are evident.

There are numerous significant correlation coefficients and some striking relationships between stimulus conditions, type of dependent measure and number of intensity levels. All of the correlations are positive and approximately 50% of the correlations are significant. In the one signal level condition, hits and response latency discriminate reliably between sense mode and coupling conditions. These correlations are significant and highly consistent. Between the visual tasks in the one signal level condition there is a remarkably high correlation of β values which reflects a very consistent mode of responding for the visual modality.

TABLE 4

Correlations Between Stimulus Conditions for Conventional and Detection Measures (N = 18)

Stimulus Condition	Hits	False Alarms	d'	β	Latency
	One Intensity Level				
Auditory vs closely coupled visual	.65**	.15	.34	.33	.76**
Auditory vs loosely coupled visual	.48*	.21	.27	.32	.75**
Closely vs loosely coupled visual	.62**	.43	.47**	.92**	.70**
	Three Intensity Level				
Auditory vs closely coupled visual	.63**	.32	.58*	.54*	.10
Auditory vs loosely coupled visual	.64**	.22	.50	.34	.11
Closely vs loosely coupled visual	.38	.61**	.32	.10	.07

Pearson product-moment correlations.

Critical values for two-tailed tests are as follows: $r_{.10} = .40$; $r_{.05} = .468$; $r_{.01} = .590$

*$p < .05$

**$p < .01$

Number of Signal Intensities. Surprisingly few studies of vigilance performance have manipulated signal variables, such as intensity and duration, over a significant range (33). C. H. Baker (4) did vary signal duration within a vigilance session and Loeb and Binford (37) varied signal intensities between sessions. However, to our knowledge, signal intensity has not been manipulated within a vigilance session.

A Lindquist Type VI mixed analysis was performed on the data to determine the differences between one and three signal level groups.

Two separate analyses were computed for Hits: (1) total number of hits and (2) number of hits on the Moderate intensity level converted to percentages for each group.

There were no significant differences between groups on any of the five dependent measures. This finding was anticipated primarily because of the following factors: first, preliminary data equated difficulty of discrimination; secondly, the methodological difficulties of isolating those effects specifically associated with the Moderate intensity level in the three signal level group; and third, the inter-subject comparisons are usually much less precise in a mixed factorial design. Most of the variance attributable to stimulus conditions, time blocks and respective interactions were highly significant. An examination of these interactions may provide valuable insight into the complex relationships involved in presenting several intensity levels as critical signals.

Similar results were obtained from the two separate analyses of Hits. Main effects for stimulus conditions and time blocks were significant ($p < .001$). The Time Blocks x Groups interaction ($p < .025$) is plotted in Figure 11. There is a significant decline in mean number

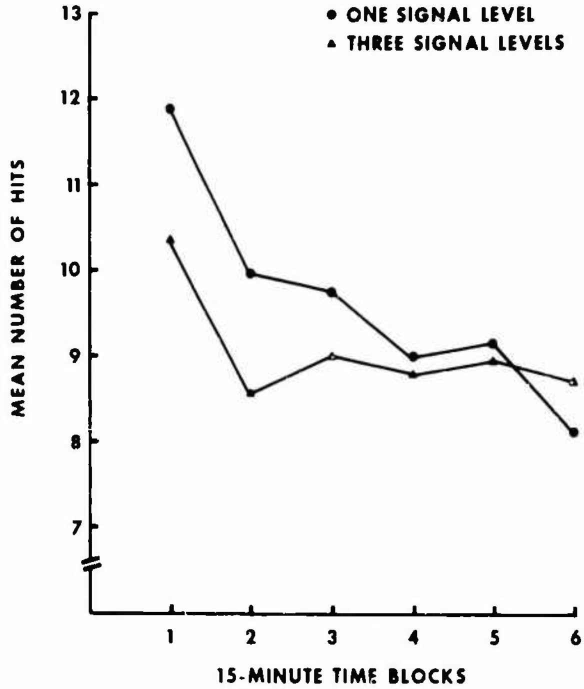

Fig. 11. Time Blocks x Groups interaction for mean number of hits.

of hits, with a sharp decrease in performance during the first 30 min for both groups. However, while the one signal level group exhibits a continual decline in detections, subjects attending to three signal intensities maintain a consistent level of performance for the remainder of the vigilance session. A plot of the Stimulus Conditions x Time Blocks interaction ($p < .01$) is very similar to Figures 1 and 2. Subjects detected more signals in the auditory condition, and the fewest number of hits in the loosely coupled visual condition. Performance in the closely coupled visual task occupied an intermediate position, but clearly exhibited the greatest variability across time periods.

False alarms was the only measure with a Stimulus Condition x Groups interaction ($p < .025$). Main effects for stimulus conditions and time blocks were highly significant ($p < .001$). There was a sharp decline in false alarms during the first 30 min of the session followed by a more or less gradual decline during the remaining time periods.

Main effects for stimulus conditions ($p < .05$) and time blocks ($p < .001$) are both significant for response latency. There were no interactions, therefore a plot of these main effects would be quite similar to Figures 5 and 6. There is a significant increase in response latency with time on task, regardless of stimulus conditions or number of signal intensities.

On the sensitivity measure (d'), main effects for stimulus conditions was significant ($p < .001$); however, main effects for time blocks was not significant. This is because the two closely coupled tasks show a gradual decline in sensitivity for one signal intensity but a corresponding average increase for three signal intensities (Figs. 7 and 8). Curves plotted for the Stimulus Conditions x Time Blocks interaction ($p < .05$) would be quite similar to the above-mentioned illustrations of mean d' values. The Time Blocks x Groups interaction ($p < .001$) is presented in Figure 12 (next page). By summing within stimulus conditions, it is readily apparent that the techniques utilized in this experiment for equating over-all intensity levels between groups was largely successful. Equating sensitivity levels between stimulus conditions for each intensity level is infinitely more difficult.

Results for mean criterion indices (log β) are very similar to mean response latency. There are main effects for stimulus conditions and time blocks ($p < .001$) and no interactions. There was a uniform tendency to adopt a more conservative mode of responding with increasing time on task.

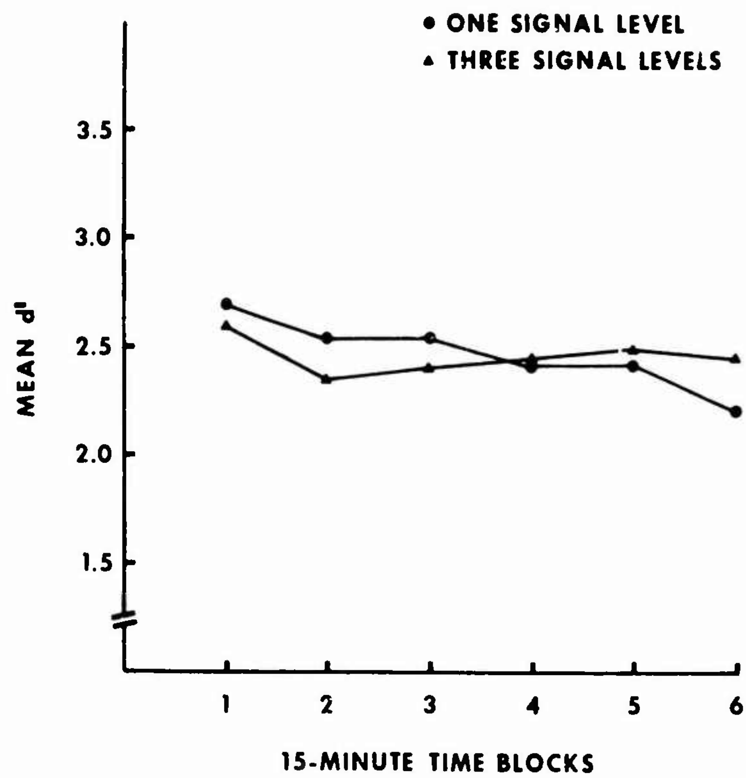

Fig. 12. Time Blocks x Groups interaction for over-all mean sensitivity levels.

DISCUSSION

The interpretation of these data and the generality of the findings are somewhat restricted due to current methodological problems associated with this area of research.

First, equating stimulus conditions between sense modes continues to be a difficult task, whether one uses psychophysical methods (12) or the more recent detection measures (26). In the majority of detection experiments, thousands of observations are obtained on a few, highly trained subjects. This technique has permitted very precise estimates of sensitivity for detection experiments, but has its limitations for vigilance research. Since we are often interested in the performance of large groups of relatively naive observers, several different groups of subjects were used during the preliminary study and the main experiment. Even so, it was possible to equate mean sensitivity levels (d') between stimulus conditions within a small range, e.g., Difficult intensity level ± .35; Moderate intensity

level ± .11; and Easy intensity level ± .23. Average sensitivity levels were also maintained within a small range (± .11) for each stimulus condition (Difficult, Moderate, and Easy sensitivity values combined). Equating stimulus conditions between sense modes on the basis of mean sensitivity values appears to be a most useful and promising technique.

Secondly, what is the best method for computing detection measures for vigilance data? An effort was made to reduce the magnitude of the problem by (1) specifying an observation interval to avoid the complications inherent in those designs which utilize undefined observation intervals (22, 25) and (2) using a relatively high signal rate in an attempt to generate an adequate number of false alarms. Since several investigations (44) have reported similar trends for high and low signal rates, the use of a high signal rate to study the vigilance decrement seems justified. Nevertheless, the absence of false alarms and 0% or 100% performance on number of detections, does require an approximation of detectability indices computed from detection and false alarm probabilities. Jerison, et al (34) discuss this persistent problem and present a method for treatment of these data. A somewhat similar procedure was adopted in this experiment to provide estimates of d' and β.

Third, if several intensity levels are presented during a vigilance session, how can one determine which false alarms are associated with a specific intensity level? This problem has not been resolved, and therefore average detection measures were computed for the three intensity level condition. Since the average sensitivity level within and between each stimulus condition was carefully equated, this technique seems defensible. At any rate, if the theory of signal detectability (TSD) is to be a substantive theory of human performance, then it must be applicable to situations studied in the laboratory and these situations typically involve the detection of several signal intensities in the same session.

There is a strong need for a description of the conditions under which decrements will and will not occur, both as a function of stimulus conditions and of the response measures employed (6). A fairly large literature testifies to the fact that there is a decrement in performance, as measured by the proportion of correct detections, or hits, as the watch progresses. In each of the experiments that included an attempt to estimate the false-alarm probability, this probability was found to decrease along with the hit probability (26, 38). Decrements in performance have occurred in different sensory modes over a wide range of signal rates (17, 28, 39, 44). In this experiment,

there was a significant decline in the number of hits and false alarms with increasing time on task, regardless of sense mode, coupling conditions, or the number of signal intensities presented to the observer. The finding that the detection probability for the auditory signals was higher than for the visual signals is in agreement with the results of many studies (5, 51, 55), even when attempts have been made to equate difficulty level between visual and auditory (17) or auditory and cutaneous (39) sense modes. Further, in this study, the rank order of stimulus conditions was fairly uniform. Subjects detected most signals in the auditory task, an intermediate number in the closely coupled visual task, and achieved the fewest number of hits in the loosely coupled visual task. Of particular relevance is the noticeable inverse relationship in the rank order of stimulus conditions for mean number of false alarms. Although difficulty of discrimination appears to determine the initial and over-all levels of performance for each stimulus condition, the significance of the progressive decline in hits and false alarms is not known (17, 19, 37). It may be due to a progressive decline in responding, but this fact has not been conclusively demonstrated.

A summary of the use of reaction time or response latency as a measure of perceptual vigilance has been recently reported in the literature (14). In general, the experimental evidence confirms the prediction that when detection rate decreases, reaction time increases; and that as fewer signals are detected, the observer takes longer to respond to those signals which he does detect (38). Differential effects have been reported for difficulty of discrimination (37) and as a function of the frequency of auditory signals (7).

The consistent rank order relationships between the stimulus conditions of this experiment clearly suggest that there are uniform trends among conventional response measures. The auditory task has the greatest number of hits, fewest false alarms, and the shortest response time. Conversely, the loosely coupled visual task was characterized by the fewest number of hits, most false alarms and the longest latency.

Recently, there have been several attempts to apply signal detection theory to the vigilance situation. A direct application of TSD is feasible by considering vigilance effects to be due to changes in criterion by the observer or to changes in signal or noise variance with time. Results with different sense modes have been largely contradictory. Visual experiments reported by Mackworth and Taylor (44) indicate that the detectability of the signal decreases with time on watch. Further, the decrease in log d' from its initial value was linearly

related to the square root of the time on watch and the rate of decline was independent of most experimental variables employed. Broadbent and Gregory (12) found no significant change in d' for either a visual or auditory task but an increase in the observer's criterion during a vigil. However, the increase in caution was highly dependent upon the initial mode of responding, e.g., cautious observers became even more conservative; whereas, liberal observers maintained the same criterion throughout the vigilance session. Results from additional research with auditory signals (8, 37, 38) have not been conclusive. Initially, these investigators obtained data explicable in terms of changes in criteria for responding. There was some reason to believe, however, that sensitivity was also changing. Their most recent publication (8) reported a small decrease in d' and a slight increase in β within sessions. Although a direct comparison of visual and auditory experiments is most difficult due to differences in experimental and computational procedures, it has been suggested that there may be at least two kinds of vigilance "decrements" produced by different underlying mechanisms. Further, it has been argued that type of signal or mode was the more important variable and that as a result of the nature of the "coupling", the auditory display was more demanding of the subject's attention. The present experiment was designed to examine these various hypotheses.

If the critical signal remains at a constant signal-to-noise intensity ratio, there is a significant decline in sensitivity with increasing time on task for the closely coupled tasks, regardless of the sense mode involved. However, sensitivity associated with a loosely coupled visual task remained fairly stable throughout the vigilance session. This evidence is not compatible with the explicit assumptions of conditioning, reinforcement or observing response theory. In a loosely coupled task, the observer may easily make a response incompatible with observation of the display. It has been postulated that non-reinforcement of such responses produces a decline in observing responses, thereby reducing the number of detections (31, 32, 34). ROC curves derived from this kind of data should reflect decrements in sensitivity with time (38). In the present experiment, however, there was no significant decline in sensitivity on the loosely coupled visual task. An alternate explanation, in terms of neural mechanisms, e.g., habituation (50), seems plausible. Specifically, it is postulated that the irrelevant observing responses may actually inhibit habituation effects and thereby permit a relatively stable sensitivity level to be maintained throughout the vigilance session. The habituation hypothesis is certainly consistent with the data of those subjects who were required to detect three signal-to-noise intensity ratios as critical signals. In

this experimental condition, there was no significant decline in sensitivity for any of the vigilance tasks. Results of this study may be viewed as somewhat analogous to research on multiple displays and response complexity. Although these data have rarely been analyzed in TSD terms, it is generally agreed that the vigilance decrement is negligible (1, 56). These investigators found damaging decrements for simple tasks, but demonstrated that the vigilance decrement can be virtually eliminated for some complex monitoring tasks. Likewise, in this experiment, observing for three intensity levels prevented a decline in sensitivity with time on task. At least, that portion of the decrement due to changes in sensitivity was reduced. The use of multiple intensity levels as an effective means for sustaining alertness finds theoretical support from the "filter theory" hypothesis (10) and the arousal or activation hypothesis (1, 24). Finally, from a pragmatic viewpoint, it may not be necessary to alternate presentations to different sense modes (27) or to present redundant signal information (5, 18) in order to achieve improved detection performance.

The subjects' criteria of what constitutes a signal seems to exert a major influence in monitoring tasks. In this experiment, criterion values increased significantly during the vigilance session, irrespective of number of signal intensities, sense mode or coupling conditions. There is a tendency, therefore, for the observer to adopt a more conservative mode of responding with increasing time on task. In signal detection theory, sensitivity and criterion are fixed for a given set of initial conditions. The theory does not specify how an observer might modify estimates of the initial conditions. However, it is obvious that such changes would have relatively simple consequences. If β increases, then there would be a corresponding decrease in hits and false alarms, a fact which is summarized in the operating characteristic, or isosensitivity curve. The Egan, et al (22) hypothesis of criterion change considers both the progressive change in hits and false detections, and the results of this experiment agree with that prediction. A systematic set of experiments should be performed to determine those factors influencing criterion changes within a vigilance session. Until such definitive tests are accomplished, it would be presumptuous to postulate explanatory concepts.

One of the major objectives of this study was to demonstrate the importance of "coupling" effects in vigilance research (13, 19, 23, 38). Coupling has always been confounded with sense modality and has not been manipulated as an experimental variable. Its effects have been largely suggestive, as a post hoc explanation of the disparate results between sense modes. Therefore, a closely coupled visual task was

designed to permit an examination of both sense mode and coupling effects. The experimental design was not symmetrical, due to a lack of an appropriate loosely coupled auditory task. Nevertheless, orthogonal comparisons of that portion of the variance due to stimulus conditions, clearly establish "coupling" effects as a critical independent variable. At one intensity level, "coupling" effects account for a significant portion of the variance in four out of five measures; whereas, sense mode effects are largely restricted to the detection measures, d' and β. The "coupling" effects are even more dramatic if subjects are required to observe for three intensity levels. In this experimental condition, sense mode differences do not account for a significant portion of the variance on any of the five response measures; whereas, "coupling" effects were significant for false alarms, d' and β values. It would appear that a lack of control of "coupling" effects rather than sense mode specificity may have confounded the interpretation of the results between visual and auditory tasks. Additionally, the hypothesis of two kinds of vigilance decrements produced by different underlying mechanisms may be incorrect. The implication of these results is that the factors operating to cause a decrement in vigilance performance probably are central in origin. This suggests that the mechanics underlying the vigilance decrement are not associated specifically with characteristics of the receptors themselves, but rather are to be found in neural centers common to all modes of responding.

The generality of the concept of vigilance has been frequently questioned, primarily due to low correlations between performance measures for visual and auditory monitoring tasks. According to Buckner, et al (17), the correlation between individual performances on the visual and auditory tasks was .30 under alerted conditions and .24 under watch conditions, indicating that individual performances were highly mode-specific. It was evident that performance on one mode could not be predicted accurately from performance on the other, in spite of high performance reliabilities within mode. The reasons for the sense mode specific differences among subjects has long been recognized as an important target for research. Jerison and Pickett (32) account for the low correlations on the assumption that auditory and visual tasks share a common component of observing response variance with respect to the neural attention systems, but that visual monitoring has a major special factor associated with orientation responses. In other words, correlations among vigilance tasks should be related to the similarity of type of observing behavior required. Since this experiment has emphasized "coupling" effects, an attempt was made to examine the observing response hypothesis. It was also apparent that the choice of a dependent measure may have

been a critical variable in prior research. Therefore, after signal detection and false alarm rates were tabulated for each condition for each observer, the corresponding normal deviates and ordinates of the normal curve were obtained, and from these the signal detection parameters reflecting sensitivity (d') and conservatism in responding (β) were computed. These detection measures were used to examine the hypothesis of common factors underlying efficiency of detection and common response biases involved in the detection of visual and auditory signals. Even if sensitivity is not correlated across modalities, it is reasonable to hypothesize that a person adopting a particular criterion for responding in one modality will in all probability do so when he responds in another modality.

Numerous significant correlation coefficients were obtained but it is difficult to identify and isolate uniform effects for a specific factor. This is not surprising, since many of the so-called independent variables of vigilance performance are interdependent (32). In addition, a proper analysis of the correlations between TSD and conventional measures required more than a simple application of TSD notions in which d' is treated as a measure of signal detectability and β as a measure of the criterion (34, 38, 47). Although a precise interpretation of these correlations of performance cannot be attempted at this time, there are some important, discernible relationships. First, all of the correlations are positive and approximately 50% of the correlations are significant ($p < .01$). Within a factor analytic framework, we would at least assume that all of these correlations are measuring some common variance. Secondly, five of the six correlations for total number of hits are significant, with the last correlation approaching significance. Performance can be predicted between both sense mode and coupling conditions, using one or three intensity levels as critical signals. Third, at one intensity level, mean response latency discriminates reliably between sense mode and "coupling" conditions. All of these correlations are significant and highly consistent. Fourth, in the one intensity level condition, performance between visual tasks could be predicted on all five dependent measures. The highly significant correlation between criterion values reflects a consistent mode of responding across tasks involving the visual modality. The moderate, but not statistically significant, correlations of d' and β between auditory and visual tasks should not be ignored. These cross-modality correlations are particularly interesting and potentially of theoretical importance. It may signify that there is a cognitive or other central component of signal detection transcending modalities.

Due to methodological problems, a concise interpretation of correlations of performance for the three intensity level condition is not feasible for false alarms, latency, d' and β. Until more reliable techniques are available, an analysis of the effects for each intensity increment would be inappropriate.

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13. ABSTRACT

This investigation examined the performance of thirty-six subjects on three 90-minute vigilance tasks. Response measures for signals were available in three basic forms: hits, false alarms, and response latency. In addition, parameters of signal detection, d' and β were derived from the data. (U)

There was a significant decrease in hits and false alarms with increasing time on task, regardless of sense mode and coupling conditions, or the number of signal intensities. In general, when detection rate decreased, reaction time increased. The consistent sequential relationship between the stimulus conditions suggests that there are uniform trends among conventional response measures. (U)

There was a significant decline in sensitivity (d') with increasing time on task for the closely coupled tasks, regardless of sense mode involved, but d' remained fairly stable for the loosely coupled visual task. In this experiment, β values increased significantly for all vigilance tasks. There is a tendency, therefore, for the observer to adopt a more conservative mode of responding with increasing time on task. (U)

Orthogonal comparisons of that portion of the variance due to stimulus conditions clearly establish coupling effects as a critical independent variable. Numerous significant correlation coefficients of vigilance performance are reported and current methodological problems associated with this area of research are discussed in detail. (U)

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Vigilance						
Audition						
Vision						
Monitoring						
Inter-Sensory Correlations						
Coupling						
Single vs Multiple Signals						